APPENDIX A

Critical Assembly Descriptions

APPENDIX A
CRITICAL ASSEMBLY DESCRIPTIONS

This appendix provides a brief description of Technical Area (TA)-18 critical assembly machines and their characteristics. Descriptions of the critical assembly machines are limited to those that are currently operating and would be relocated under the TA-18 relocation alternatives.

A.1 CRITICAL ASSEMBLY MACHINES

The critical assemblies, or assembly machines, at TA-18 have been in existence since 1946 (DOE 2001). Since then, many thousands of criticality measurements have been made on assemblies of fissile material (uranium-235, uranium-233, and plutonium-239) in various configurations, including the nitrate, sulfate, fluoride, carbide, and oxide chemical compositions and the solid, liquid, and gaseous states. At present, the complex consists of five operating machines that include roughly five types of assemblies:

- Benchmark critical assemblies (Flattop)
- Assembly machines used to remotely assemble critical experiments (Comet and Planet)
- Solution assemblies in which the fuel is a fissile solution (Solution High-Energy Burst Assembly [SHEBA])
- Prototype reactor assemblies that operate at low power without the need for heat-rejection systems
- Fast-burst assemblies for producing fast neutron pulses (Godiva)

The critical assemblies at TA-18 are a unique category of nuclear research reactors. The critical assemblies, are clearly classified as Category B research reactors in U.S. Department of Energy (DOE) Order 5480.30, yet they share little in common with most permanently configured research reactors. Some of the fundamental differences are (LANL 1998, DOE 2001):

- Critical assemblies are designed to operate at low average power (milliwatts to a few kilowatts) for short periods of time. They do not require coolant systems, which reduces the overall complexity of the assemblies.

- Critical assemblies include machines designated as fast burst reactors, (i.e., Godiva). These reactors normally operate in a pulse mode at a very high peak power, with total pulse widths on the order of 100 microseconds leading to a total energy yield per pulse of about ~1 megajoule. Each pulse operation is initiated from room temperature. Thus, these reactors share a low-energy release-rate behavior compared with the traditional critical assemblies.

- Because they operate at low average power for short periods, they do not build up a significant radiological inventory of long-lived fission products. The majority of the fission products remain within the fuel material and decay to stable isotopes. This eliminates problems with decay heat and makes the critical assemblies "walk-away" safe after a safe shutdown. Furthermore, most of the assemblies can be accessed shortly after operating with relatively minor radiation protection requirements.

As a result of these three differences, there is no need for engineered safeguards such as decay heat removal systems, emergency core coolant systems, engineered containment structures, etc. A simple confinement building to mitigate the consequences of design basis accidents is all that is needed.

The critical assemblies at TA-18 are experimental systems that are designed and reconfigured for the needs of an experimental program. Two generic classes of machines are used:

- Permanently configured assemblies with fuel and control elements mounted on the machine (Flattop, Godiva, and SHEBA)

- Critical experiment remote assembly machines that serve as stable platforms for assembling fuel components and control elements for remote operation (Comet and Planet)

Since this discussion of the operation and controls of critical assemblies uses various technical terms relevant to criticality safety, a brief discussion of the technical concepts and terms is provided below.

A critical assembly is a system of fissile material with or without a reflector (beryllium, copper, iron, etc.) in a specific shape and geometry. The critical assembly can be gradually built up by adding additional fissile material and/or reflector until this system achieves the dimensions necessary for sustaining a constant rate of fission in a chain reaction (a nuclear reaction), known as critical condition. The minimum quantity of fissile material capable of sustaining such a reaction is called the critical mass for that assembly. Critical mass is a function of the purity of the fissile material, as well as the geometry, or the shape, of the assembly.

A nuclear fission is a nuclear reaction in which an atom of fissile material absorbs a neutron causing it to split into two smaller atoms while releasing energy and a few neutrons. The neutrons which are released from the fission reaction are called fast neutrons because of their high energy and velocity. The probability that a fissile isotope's atom can absorb a neutron and fission is much higher if the neutron has a lower energy and velocity. Therefore, systems which are designed to optimize the fission process and sustain criticality (e.g., in a nuclear reactor) include a material called a moderator. A moderator is one or more elements with a relatively low atomic weight, such as hydrogen (water), carbon, and beryllium, which are effective at slowing down the fast neutrons emitted from the fission process. When most fast-fission neutrons collide with moderator atoms, these neutrons lose some of their energy and velocity by transferring this energy to the moderator atom. This process is similar to that of a billiard ball striking one or more other billiard balls after which the striking billiard ball has slowed down.

Critical systems use a reflector outside the fissile isotope. Neutrons produced from fission escape or leak out of the fissile isotope. These lost neutrons cannot contribute to maintaining fission reactions. A reflector is a material which returns many of these escaping neutrons back to the fissile material. Typical reflectors include steel, aluminum, beryllium, copper, and natural uranium.

When the fission chain reaction produces enough neutrons to initiate additional fissions so that this reaction becomes self-sustaining, a condition called criticality is achieved and such a system is critical. The ratio of the neutrons produced in one generation to the neutrons produced in the previous generation is called the neutron multiplication factor, or K_{eff}. For the critical system, the multiplication factor is equal to 1. If the multiplication factor of a system is less than 1, the system is called subcritical, i.e., the fission chain converges (decreases with time) and eventually ends. Conversely, if the multiplication factor is greater than 1, the system is called supercritical, i.e., the fission chain diverges (increases continuously).

Two categories of neutrons are produced from the nuclear fission process: prompt and delayed. Prompt neutrons are emitted instantaneously with the fission event and have a typical lifetime of about 0.00001 seconds. Delayed neutrons are emitted by fission products over a time period of up to approximately one minute after the fissions have occurred. Prompt neutrons constitute over 99 percent of all fission neutrons while delayed neutrons account for approximately 0.2 to 0.7 percent of all fission neutrons depending on which fissile isotope is present. For uranium-235, the delayed neutron fraction is about 0.007, and for plutonium-239 it is about 0.002. A system of fissile material can achieve a critical state using just the prompt neutrons or both the prompt and delayed neutrons. These two conditions are called prompt critical and delayed critical, respectively. On a similar basis, a fissile material system can become prompt supercritical or delayed supercritical. An important difference between these two conditions is that the longer lifetime of delayed neutrons allows a delayed supercritical system to be controlled much more easily than a prompt supercritical system. Typically, a delayed supercritical system increases fission over a time period that allows the mechanical movement of components either to control it or to shut down the fission process. A prompt supercritical system's fission rate increases too rapidly for mechanical movements to be effective. Instead, the system relies on inherent natural behavior such as fissile material temperature rise to reduce the multiplication factor below 1.

The fractional change in the neutron multiplication factor from one neutron generation to the next is known as reactivity. Reactivity is defined by the following expression: $\rho = 1 - 1/K_{eff}$. Reactivity is stated either in terms of percent change in multiplication factor as $\Delta K/K$, or in units of dollars ($) and cents (¢). A dollar reactivity is equal to the delayed neutron fraction—the fraction of all neutrons produced during nuclear fission that is delayed by up to about one minute after the fission occurs. The reactivity cent is one hundredth of a reactivity dollar. The addition of negative reactivity to a critical system results in a subcritical condition. The addition of positive reactivity to a critical system results in a supercritical condition. When a system has a reactivity of exactly one dollar, the system is called prompt-critical. The addition of sufficient positive reactivity to a subcritical system can result in a critical condition. Reactivity can be determined by measuring the change in neutron emission rate over time from an array of fissile material(s).

A fissile material system's multiplication factor can be determined by measuring its neutron generation. This is accomplished by placing a known neutron source inside the fissile material system and measuring the rate of neutrons emanating from the outside surface of the system. The increase in the number of neutrons, called the multiplication factor or M, compared to the number of neutrons emitted by the source can be converted into the system's multiplication factor, K_{eff}, by the formula:

$$K_{eff} = 1 - 1/M$$

Thus a system with a neutron multiplication of 100 indicates that its K_{eff}=0.99, (1-1/100).

A.1.1 Flattop

Flattop is located in Building 32 (CASA 2) at TA-18. The Flattop assembly has interchangeable spherical cores of highly enriched uranium [93 percent enriched in uranium-235, denoted as U(93)] metal or plutonium-239 metal, surrounded (during remote operation) by a reflector of thick natural (normal) uranium metal. The reflector is subdivided into a stationary hemisphere, into which the core is recessed, and two movable quadrants. Three natural uranium control rods, one large and two small, enter the stationary hemisphere from below. The large control rod is worth from $1.1 for a uranium-235 core to $1.6 for a plutonium-239 core, and the two small control rods are worth $0.26 for a uranium-235 core to $0.4 for a plutonium-239 core. Upon shutdown, also called scram, both quadrants of the reflector retract rapidly to the normal "disassembled" condition. Flattop is used for fundamental reactor physics studies and, by irradiation in the known neutron spectra, to provide samples for radiochemical research. **Figure A–1** and **Figure A–2** show the general structure of Flattop. Flattop is approximately 2.4 × 1.8 × 1.5 meters (8 × 6 × 5 feet) in size and operates at a low average power without the need for external cooling.

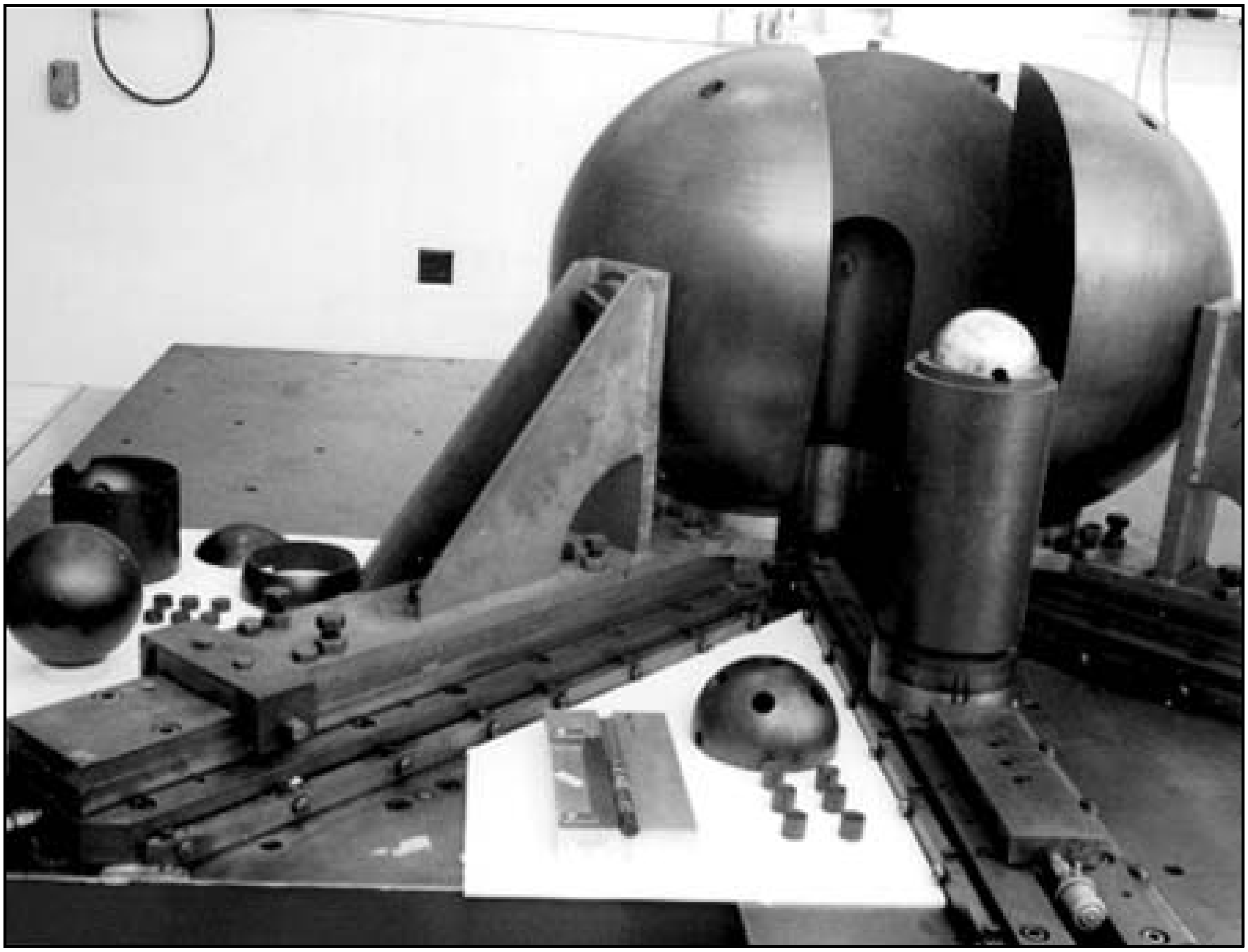

Figure A–1 Flattop Benchmark Assembly

Figure A–2 shows a schematic of a typical Flattop assembly. It consists of a core (a sphere) of fissile material at the center of a sphere of a natural uranium reflector (made out of three blocks). The core is supported on its own natural uranium pedestal, which is mounted on a keyed track with manual control for positioning the assembled core in the stationary hemisphere of a natural uranium reflector. Closure of the movable reflector quarter spheres (quadrants), known as safety block A and B, and insertion of the control rods are done remotely from the control room. The scram action (shutdown mechanism) causes the quarter-sphere safety blocks to disassemble and retract at a graded rate. The initial separation, in the first centimeter (0.4 inches), provides a reactivity withdrawal of $2.3 per block. Then the rate at which the safety blocks separate would be one tenth of the speed during the first separation. These blocks are operated by an Alternating current (Ac)-driven hydraulic pressure system, backed by two independent nitrogen gas accumulators to ensure positive scram in the event of loss of electrical power. The control rod drives are Ac-powered and do not require loss-of-power backup.

A horizontal hole (known as a glory hole) through the center of the stationary hemisphere reflector and the core provides access for irradiation samples and detectors to the central zone of the assembly. The pedestal where the fissile core sits contains many voids (cavities) that may be filled with either natural uranium or highly enriched uranium buttons to compensate for the various glory hole configurations.

The uranium and plutonium core masses (without the mass adjustment buttons and glory pieces) weigh 18 and 6 kilograms (39.7 and 13.2 pounds), respectively. The addition of mass adjustment buttons is insufficient to exceed the critical mass for the unreflected core. The cores are stored in the CASA 2 vault

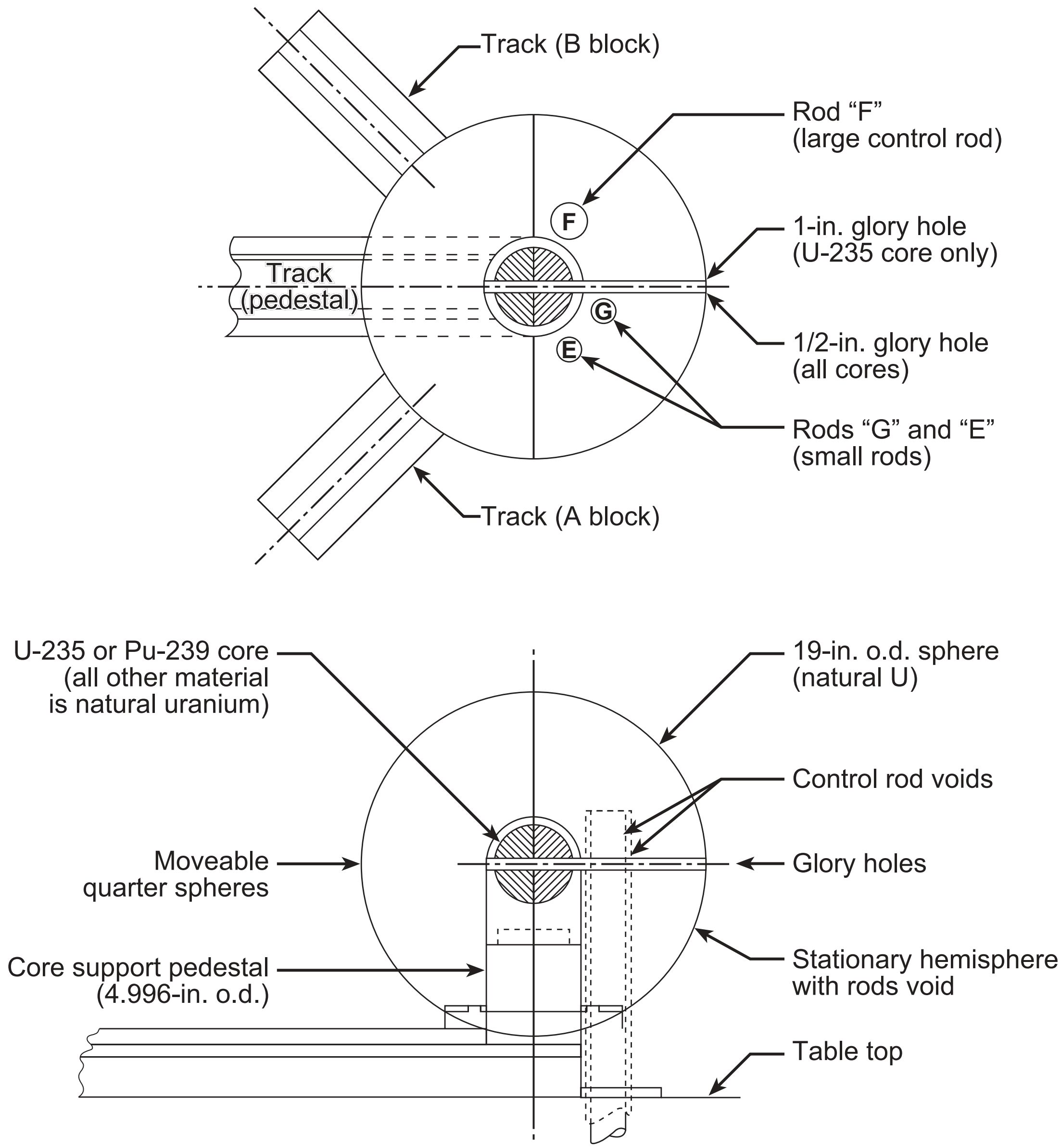

Figure A–2 Schematic of Flattop Assembly

in a criticality safe configuration when Flattop is not operating. The plutonium core is stored in heat sinks to dissipate heat from spontaneous fission decay of plutonium-240 (which constitutes about 5 percent of the total plutonium).

A.1.2 Godiva

Godiva is a fast-burst assembly with a fuel mass of 65.4 kilograms (144 pounds) of highly enriched uranium. Godiva is the fourth in a series of basically bare, unreflected, fast-burst assemblies with similar characteristics. Godiva is primarily an irradiation assembly, although its original purpose was to test design features, including material selection, that are expected to increase resistance to shock damage. The

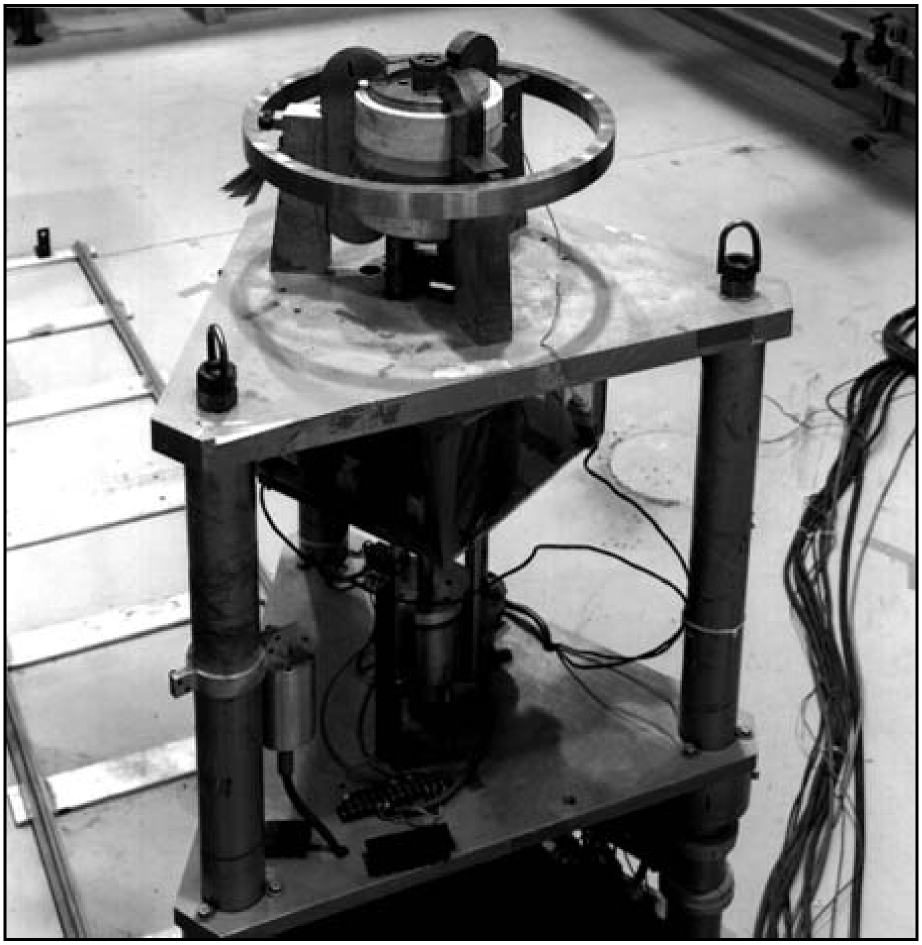

Figure A–3 Godiva (shown without optional cover)

assembly has fixed core components and a permanent structural base, (see **Figure A–3**). The entire Godiva assembly is approximately 0.90 × 1.2 × 3 meters (3 × 4 × 10 feet) tall in size. It is secured in a special vault in TA-18 Building 116 (CASA 3), and is moved on aluminum tracks from the vault to the test area. Power, control, and instrumentation circuits for Godiva are provided by an umbilical panel that physically attaches to the machine. After the test, this panel is removed by remote activation. A winch cable attached to the assembly cart is actuated, pulling the assembly into the vault. The vault door is closed and locked by command from the control room.

Figure A–4 shows the Godiva fuel components and support system. The Godiva fuel is enriched uranium alloyed with 1.5 percent molybdenum by weight. Fuel components are all aluminum-ion plated. Three external C-shaped clamps fabricated from high performance maraging steel fasten the stack of fuel component rings. The five major uranium-molybdenum alloy subsections of Godiva (stationary head and movable safety block and three control rods [two shim rods and one burst rod]) form an essentially unreflected cylinder when brought together remotely. Delayed criticality is attained when the safety block is inserted by adjustment of two uranium control rods (each worth about $1.5) that enter the head. From this state, a burst may be produced by sudden insertion of an interlocked U(93) burst rod with a reactivity worth of about $1, allowing a further adjustment of control-rod position. Thermal expansion of the fuel components produces a shock which terminates the burst. The safety block is threaded onto a stainless steel support mandrel at the lower end of the core so that thermal expansion exerts a downward thrust on the support shaft, opening a magnetic clutch to provide shock-induced trip. The production of a burst of known magnitude involves a well-defined cycle including a delayed critical check, retraction of the safety block to allow delay of the neutron population, and control adjustment to trim excess reactivity as required for the desired burst while allowing for temperature drift, reinsertion of the safety block, and burst-rod insertion. Interlocks prevent major departures from this cycle. The burst actuates a scram signal, which deactivates a magnet that normally secures the safety block and ejects the burst rod.

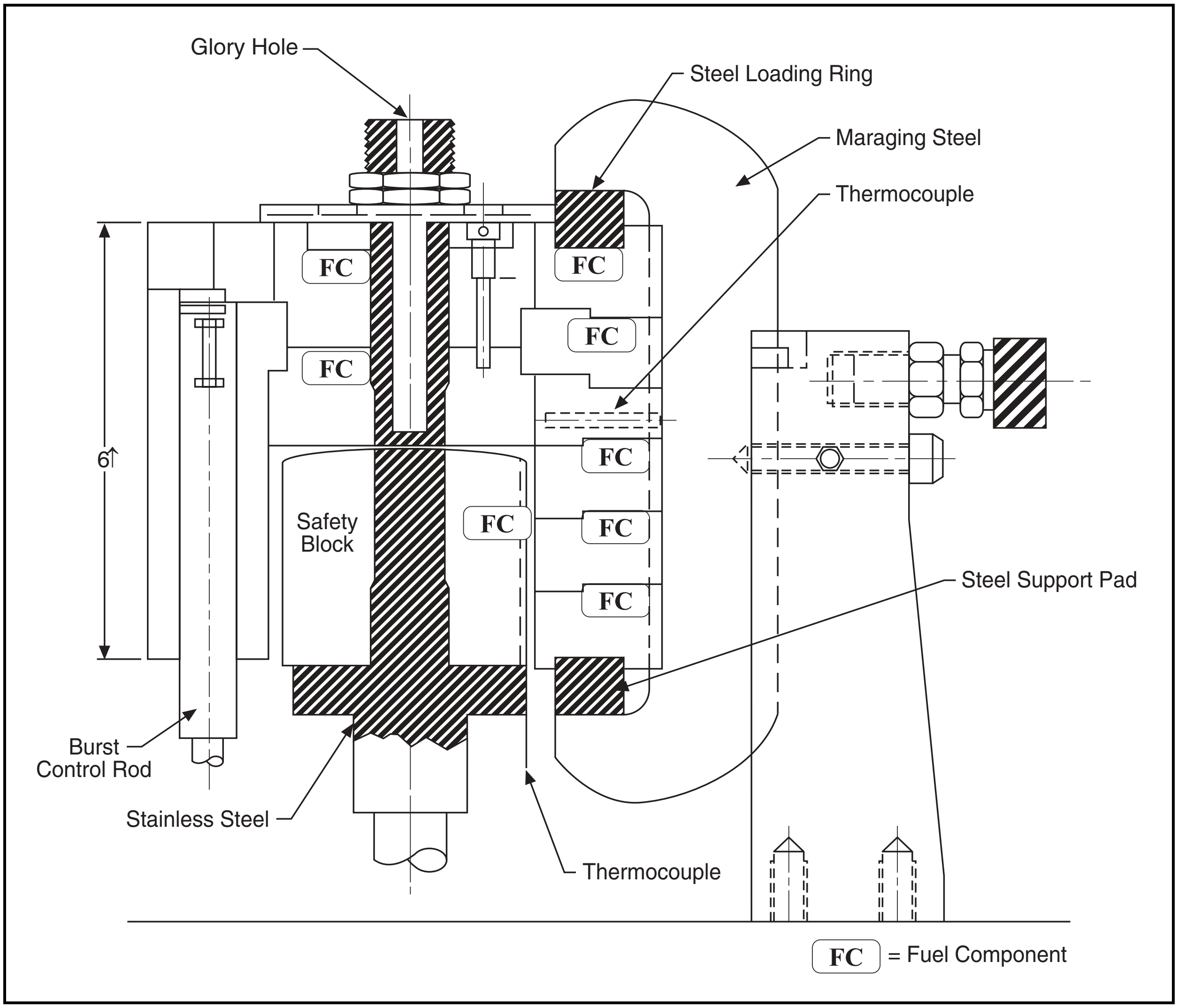

Figure A–4 Godiva Fuel Components and Support System

A.1.3 Comet

The Comet general-purpose assembly machine is a vertical lift platform located in TA-18 CASA 2, (see **Figure A–5**). The machine is designed to accommodate a wide variety of experiments in which neutron multiplication is measured as a function of separation distance between experiment components. The Comet machine may be used for criticality safety training on approach-to-critical. The Comet configuration is split into two parts, one of which is mounted in a stationary position (upper structure), while the other is located on a movable platen. The movable part of the experiment occurs in two discrete steps: actuation of a hydraulic lift and completion of motion by a stepping motor (fine adjustment). The entire assembly is 1.2 × 1.2 × 3.6 meters (4 × 4 × 12 feet) in size with its reflector in place. **Figure A–6** shows a schematic of the Comet assembly machine without reflector.

The current fuel configuration uses unclad enriched uranium circular plates approximately 0.31 centimeters (0.125 inches) thick, separated by plates of graphite approximately 1 centimeter (0.39 inches) thick. Proposed future fuel for the present experiment may include plutonium plates with a total mass of about 200 kilograms (441 pounds) or other fuel elements. Configurations may also include other geometric combinations of fissile material and interstitial materials. The Comet reflector, like the fuel, can be arranged

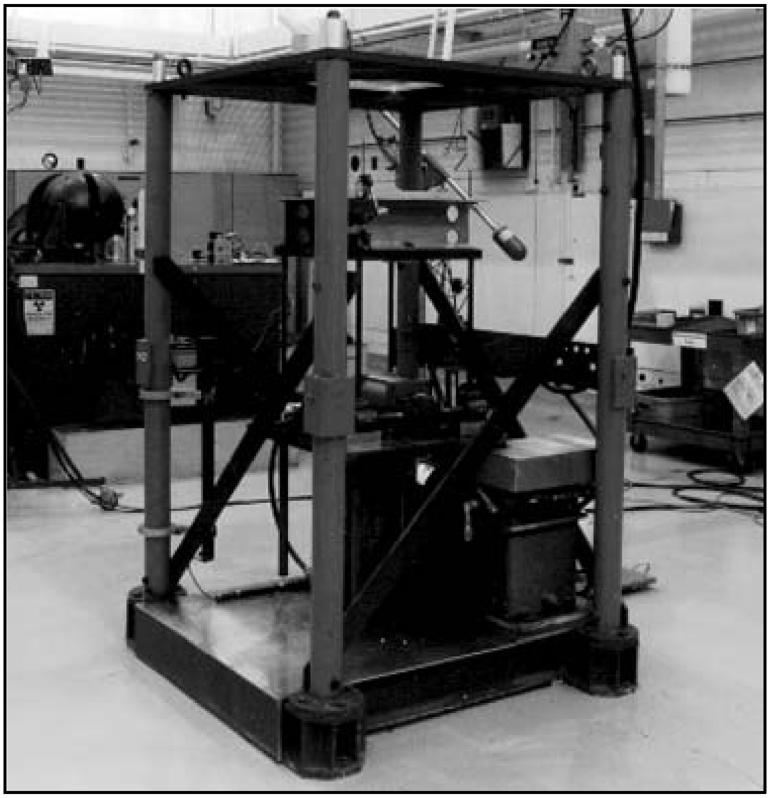

Figure A–5 Comet Assembly Machine

in various configurations. The current configuration consists of an upper region containing approximately 6,350 kilograms (14,000 pounds) of copper assembled in blocks surrounding the upper fuel components. The height of the reflector is approximately 1.2 meters (47 inches) on a 0.91-meter (34-inch) base.

Comet is designed to approach or reach the condition of criticality as the lower assembly nears the upper stationary assembly. This is accomplished by first raising the movable platen hydraulically, followed by a stepper motor drive for precision positioning of the lower assembly. Nuclear operations with Comet are first supported with detailed calculations of the proposed assembly. As material (fissile and interstitial) is stacked, but well before a critical configuration, careful measurements of the partially assembled mass are taken to verify that excessive reactivity is not present. The fuel materials which can be used in Comet include uranium, plutonium, and neptunium. Test quantities can exceed 200 kilograms (441 pounds) of fissile material. Under normal scrams, both the hydraulic ram and the stepper motor move to the least reactive conditions (initial positions). Under loss of power, the valve for the hydraulic ram switches to the down position causing the hydraulic ram to move down. This downward motion is caused by gravity and assisted by a pressure accumulator in the hydraulic system.

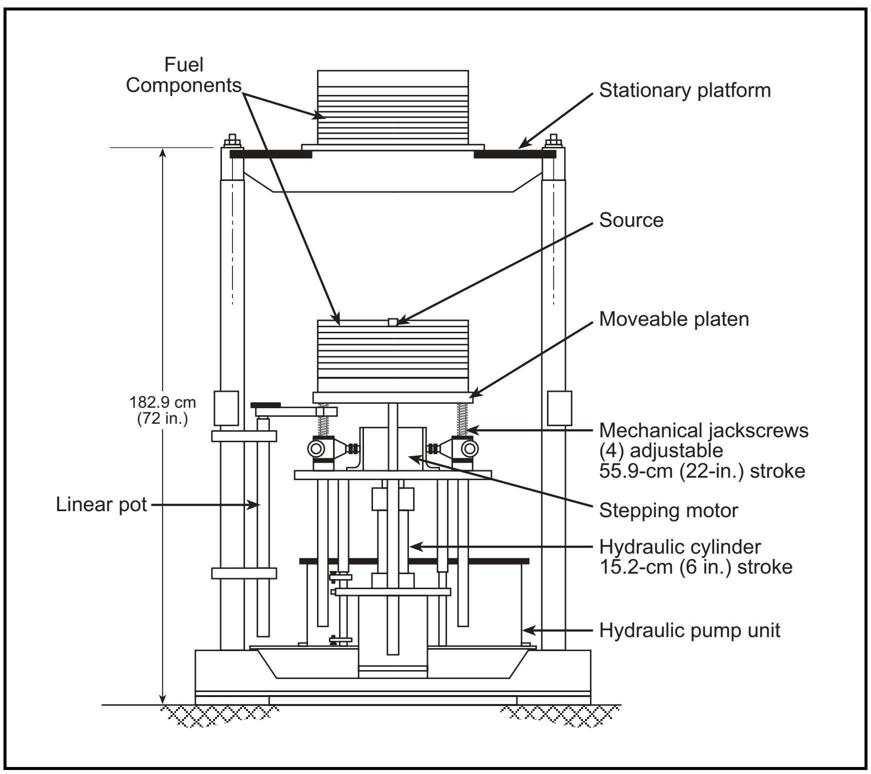

Figure A–6 Comet (shown without reflector)

A.1.4 Planet

Planet is a general-purpose, portable vertical assembly machine located in TA-18 CASA 1. Like Comet, the Planet machine uses a moveable table powered by hydraulic lift with movable platen powered by a stepping motor. A fixed (stationary) platform is mounted above the table and platen assembly. The steel frame is mounted on casters/wheels and is not rigidly attached to the CASA structure. There are retractable feet to hold the Planet in place. The planet machine has two features not found on the Comet machine: (1) a remotely adjustable positive stop on the hydraulic lift up-limit and (2) mechanical stops on the platen up-limit. The entire assembly is similar to that of Comet, i.e., 1.2 × 1.2 × 3.6 meters (4 × 4 × 12 feet) in size. **Figure A–7** illustrates the physical set up of Planet in a special criticality experiment arrangement.

Planet is used to investigate the criticality characteristics of different geometries and compositions. Both heterogeneous and homogeneous arrangements of fissile materials with different types and quantities of moderator materials can be used. Its past use includes experiments to evaluate the criticality of slab tanks filled with liquid solutions of highly enriched uranyl nitrate to simulate storage tanks at a proposed reprocessing facility.

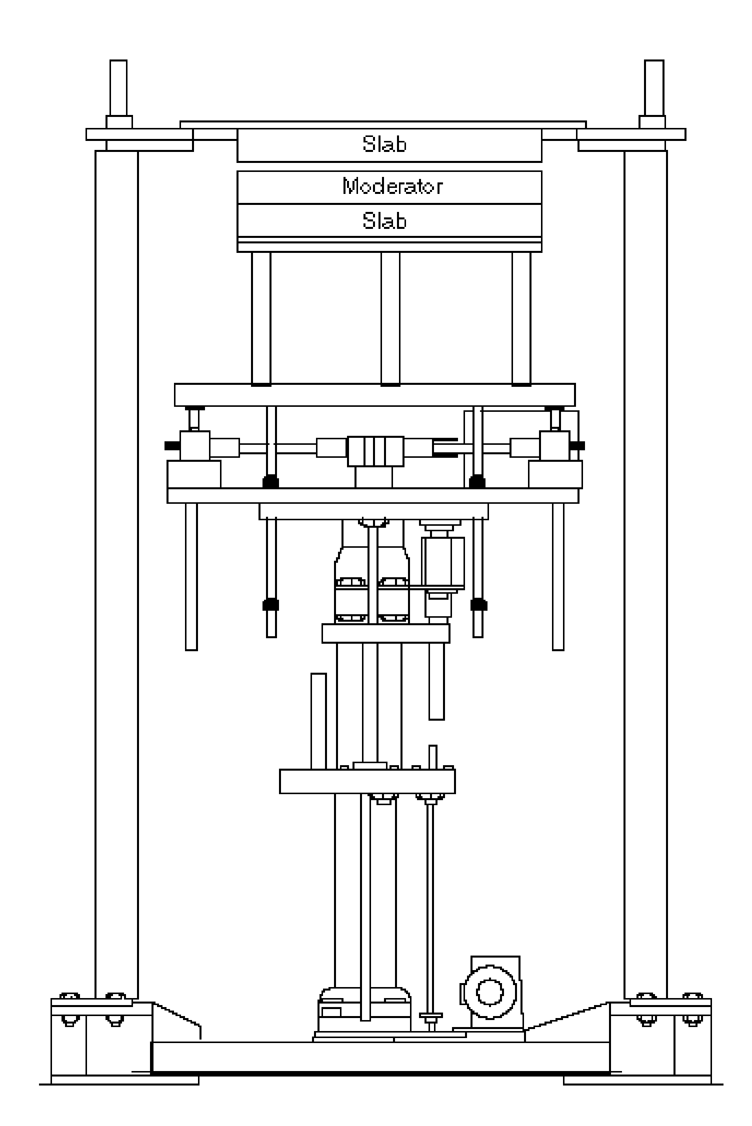

Figure A–7 Planet (in a Special Experimental Arrangement)

A hydraulic ram is the primary scram device for removing reactivity from critical assemblies on the Planet machine. Given a scram signal, the hydraulic system valves are de-energized in a manner that allows the ram to descend at a fairly rapid rate (i.e., gravity-assisted), and the stepping motor also drives the platen downward. In the event of loss of power, the hydraulic valves open to allow the ram to move down under the force of gravity. This downward movement separates the two critical-assembly segments, thereby stopping the criticality process.

Currently, one basic core type is used in Planet. The core consists of laminated foils containing 93 percent enriched uranium-235, interspersed with a variety of interstitial materials. This core loading is used in a criticality experiment performed monthly as part of the Nuclear Criticality Safety Course conducted at the Los Alamos National Laboratory (LANL). In addition, it is currently used to evaluate issues including the design of repositories for long-term disposal of nuclear materials. In the future, Planet may be fueled with weapons-grade plutonium (approximately 7 kilograms [15 pounds]), and/or with about 50 kilograms (110 pounds) of highly enriched uranium using cryogenic materials to achieve low temperatures.

A.1.5 Solution High-Energy Burst Assembly

SHEBA is operated in TA-18 Building 168 (SHEBA building). It is a simple, unreflected, fissile solution critical assembly vessel that is controlled by adding or removing solution. It was designed especially for proof testing criticality accident detection systems (see **Figure A–8** and **Figure A–9**). The detectors for criticality accident alarms were calibrated by fast-neutron leakage pulses from Godiva-like reactors (solid metal critical assemblies), whereas the majority of criticality accidents have occurred in solutions. As a thermal spectrum assembly, SHEBA generates relatively slow leakage neutrons such as those emitted by critical solutions. Fueled with either an aqueous solution of low-enriched (about 5 percent uranium-235) uranyl fluoride [$U0_2F_2$] or a solution of up to 20 percent uranium-235 enriched uranyl nitrate. SHEBA fuel requires a moderator to achieve criticality; the moderator is integral with the fuel because the fuel is a water-based solution. The critical mass of uranium-235 in SHEBA is about 4.1 kilograms (9 pounds). SHEBA is installed in a sheet metal building outside TA-18 Building 23 (CASA 1). Criticality is attained by solution-height adjustment in the critical assembly vessel whose inside diameter measures 48.9 centimeters (19.25 inches).

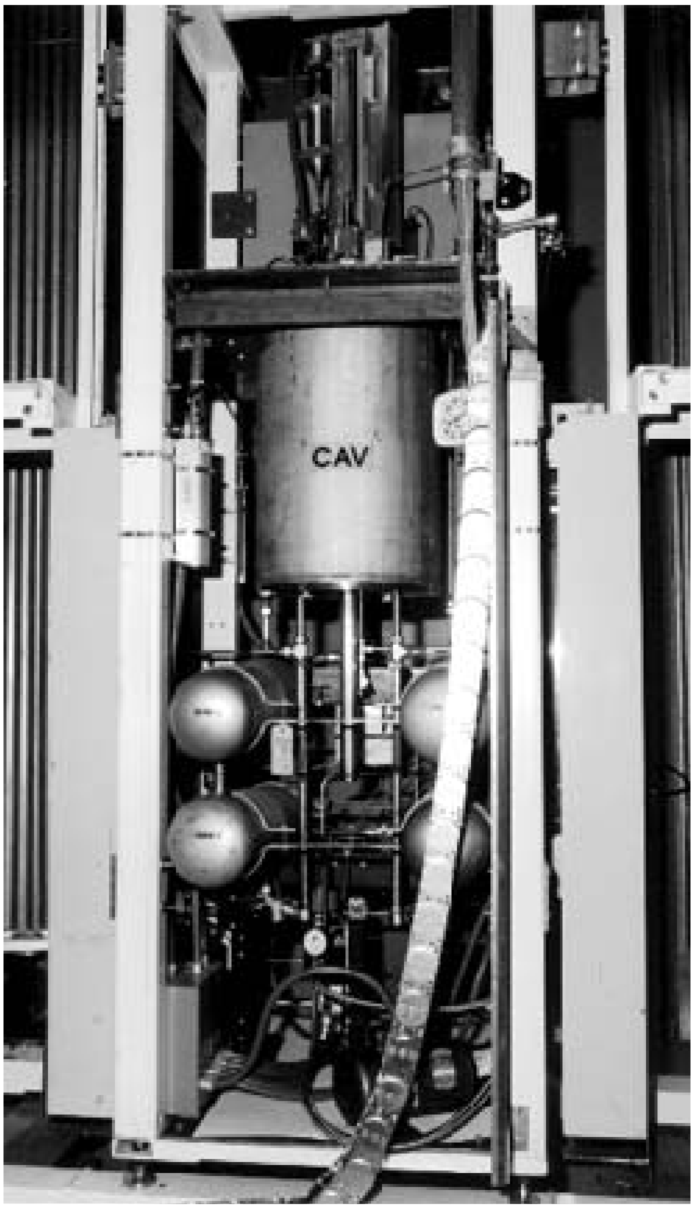

Figure A–8 SHEBA Machine

Major equipment at SHEBA includes the critical assembly vessel, four fuel storage tanks, a pumped-fuel fill system, a gravity fuel drain system, a flowing nitrogen cover gas system, and a safety rod system. The fuel solution is initially stored in four criticality-safe, stainless steel tanks. The solution is transferred to the critical assembly vessel by an AC-driven fuel feed pump. The critical assembly vessel and the storage tanks are equipped with heating and cooling jackets to maintain the solution temperature at a desired level. The jackets are attached to the building chiller system.

The nitrogen cover gas system sweeps the fission product and radiolytic gases into holding tanks after passing them through a catalytic recombiner. In the holding tanks the fission gases are allowed to decay under confinement before release. The catalytic converter recombines the radiolytic gas to maintain a noncombustible atmosphere in the holding tanks. The design pressure of the critical assembly vessel is 1.03 megapascals (150 pounds per square inch).

Shutdown is achieved by rapid draining of the uranium solution into storage cylinders. Upon scram signal, two independent scram (drain) valves open, allowing gravity draining of the fuel solution. A pneumatically operated safety rod that can drop into a 6.35-centimeter (2.5-inch)-diameter axial tube inside the critical assembly vessel is also provided as a supplement to the rapid draining shutdown process.

SHEBA has been used principally to assess and calibrate criticality accident dosimeters for a uranium enrichment plant. In addition, the assembly is used for general-purpose critical experiments and studies of the behavior of nuclear excursions in a low-enriched solution medium. It has also served as a source for skyshine (radiation scattering in air) measurements. SHEBA can also be used as training tool as part of a nuclear criticality safety class.

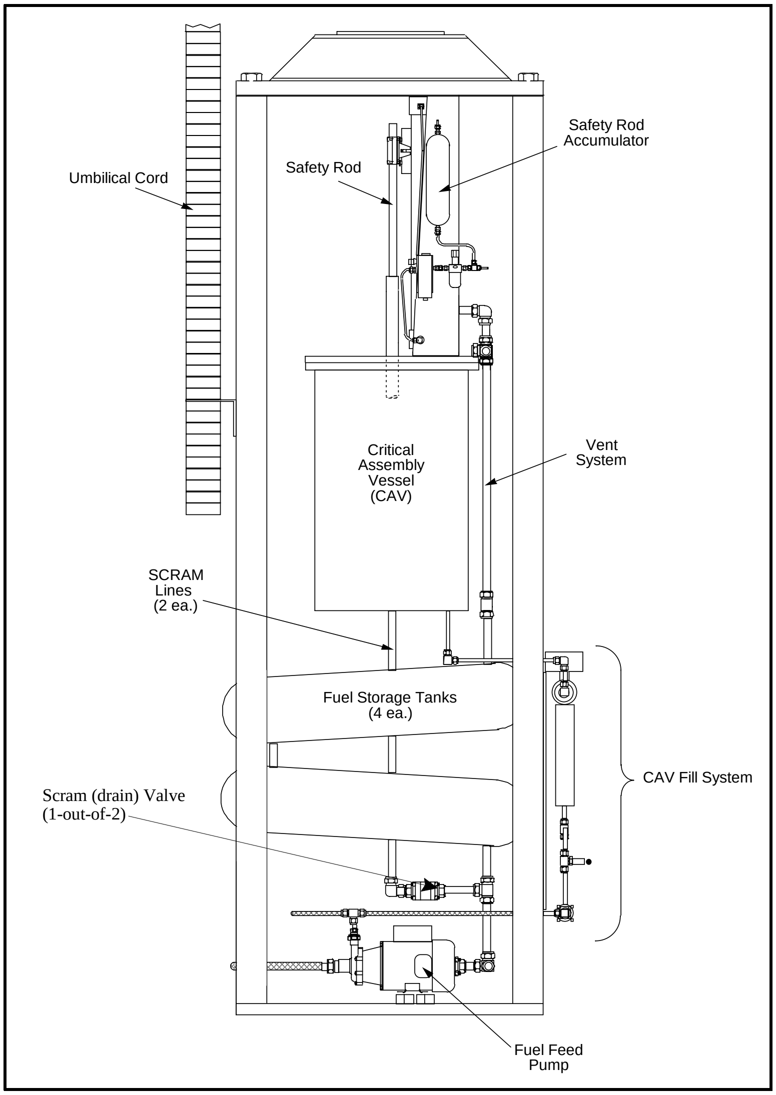

Figure A–9 Schematic of SHEBA

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